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June 8, 2015

Ms. Michele Dermer
EPA Region 9, WTR-9
75 Hawthorne St.
San Francisco, CA 94105

Subject: Updated Evaluation of Annular Pressure-Temperature Relationship
PG&E Test Injection/Withdrawal Well 1
Permit No. R9UIC-CA5-FY13-1
King Island, San Joaquin County, California

Dear Ms. Dermer:

As required under Section D.6.c of Permit No. R9UIC-CA5-FY13-1 (the Permit), PG&E has been evaluating the annular pressure-temperature relationship in Test Injection/Withdrawal Well 1 to assess the range of pressures that would be expected during normal operations and what changes might be indicative of a loss of mechanical integrity. PG&E's initial evaluation was submitted on March 27, 2015 and updated on April 1, April 17, May 1, and May 14, 2015 due to changes in injection rates and temperatures, and in response to EPA's comments on the prior submittals. The threshold for reporting annular pressure exceedances under Section D.6.b was initially set at 100 psia. After the initial operating period it was concluded that annular pressure is influenced by a complex set of variables, but is expected to remain between 30 and 600 psia during normal injection operating conditions. In addition, it was noted that a leak in the well tubing string, packer system or casing would result in a characteristic departure from the established cyclical pressure-temperature response during injection. In comments that accompanied their letter to PG&E dated April 17, 2015, EPA provided an interim upper annular pressure limit of 200 psia. Subsequent pressure excursions above the interim 200 psia reporting limit were found to be solely due to variations in annular temperature.

As part of the May 14, 2015 extended evaluation of the annular pressure-temperature relationship, PG&E requested that EPA grant an annular pressure limit of 400 psia. The EPA responded in a letter dated May 18, 2015 and accepted this revised reporting limit, stipulating that if the annulus pressure exceeds the 400 psia limit for a period greater than 24 hours, the EPA must be notified in accordance with paragraphs 2.c, 6.b, and 6.c in part II.D of the permit. During withdrawal flow testing between May 31, 2015 and June 2, 2015, the 400 psia notification limit on annular pressure was exceeded for a period greater than 24 hours. The notification limit was again exceeded during withdrawal flow testing, on June 3 and 4, 2015, but withdrawal testing was completed and the well shut in before the exceedance reached 24 hours in duration. Specifically, the following annular and injection pressures and temperatures were measured:

Time Period that Annular Pressure Exceeded 400 psia						
Start Date and Time	**End Date and Time**	**Duration of Exceedance**	**Peak Annular Pressure Date and Time**	**Peak Annular Temperature and Time**	**Tubing Head Pressure During Withdrawal**	**Peak Bottom Hole Temperature**
May 31, 2015 @11:38 hr	June 2, 2015 @17:05 hr	41.4 hours	642 psia June 1, 2015 @ 22:21 hr	93.2°F June 1, 2015 @ 14:24 hr	1560-1810 psia	125°F
June 3, 2015 @14:49 hr	June 4, 2015 @09:36 hr	18.8 hours	646 psia June 4, 2015 @ 02:48 hr	88.5°F June 4, 2015 @ 02:50 hr	0-1812 psia	126°F

PG&E notified EPA via email within 24 hours of the first reportable annular pressure exceedance (which reached the 24 hour reporting time limit on June 1). As a result of the above exceedances, PG&E has prepared an updated evaluation of the annular pressure-temperature relationship for Test Injection/Withdrawal Well 1, dated June 8, 2015.

The review and updated evaluation of the annular pressure-temperature relationship for Test Injection/Withdrawal Well 1 is attached. The updated evaluation concludes that the observed I/W well annulus pressure excursions above the 400 psia limit may be attributed solely to thermal effects and do not reflect a loss of mechanical integrity. Unlike previous evaluations where the ambient air and annulus temperatures were cycling diurnally in correlation with the annulus pressures during air injection, the recent annulus pressure excursions occurred during an extended air withdrawal cycle. Based on the evaluation, it appears that the sustained release of hot air from the reservoir resulted in heating for the annular fluids and caused the I/W well annulus pressure to rise over a longer period of time. The observed temperatures and annular pressures are consistent with the updated response function calculated based upon the available data to date. Since the suspension of withdrawal and injection on June 4, 2015, the I/W well annular pressures are continuing to decrease and are expected to eventually return to the normal range under static shut-in conditions. As of the date of this submittal, the I/W well annulus pressure was less than 170 psia.

PG&E completed its planned compression test and the I/W well will now remain shut in. We will continue to monitor the annular pressures and temperatures while the well is shut in, in accordance with the permit requirements, and will report any fluctuations outside of the range limit, or any unexpected pressure trends that do not correspond with the predicted annular pressure-temperature relationship, to EPA in accordance with Section D.6.b.

The updated evaluation of the annular pressure-temperature relationship for Test Injection/Withdrawal Well 1 is enclosed as one hard copy and as a PDF in a data CD. The document has also been uploaded to PG&E's Dropbox account, which can be accessed at the following link:

https://www.dropbox.com/sh/mf2qnl5v016e78f/AABIm-gfjIKWPpVCKe7hUgA6a?dl=0

If you have any questions regarding this submittal or require additional information, please feel free to contact me at (415) 973-6270.

Sincerely,

Mike Medeiros
Manager, Renewable Energy Development

Cc: Mr. James Walker, EPA Consultant
Mr. Michael Woods, Division of Oil, Gas and Geothermal Resources
Ms. Anne L. Olson, Central Valley Regional Water Quality Control Board

Enclosures: Updated Evaluation of Tubing/Casing Annulus Pressure Excursions

June 8, 2015

EPA UIC Permit No. R9UIC-CA5-FY13-1

FIFTH EVALUATION OF ANNULAR PRESSURE-TEMPERATURE BEHAVOIR DURING NORMAL OPERATING CONDITIONS OF TEST I/W WELL 1

This is the fifth evaluation of the annulus pressure-temperature relationship for the Test Injection/Withdrawal (I/W) Well 1. The initial evaluation submitted on March 27, 2015 and the subsequent evaluations on April 1, May 1 and May 14, 2015 have assessed the range of annulus pressures both observed and expected during normal well operations that are due to the thermal effects from changes in wellbore temperatures and injection/withdrawal rates.

In the previous PG&E evaluation submitted on May 14, 2015, it was concluded that the observed annular pressure behavior during the compression testing program operations, and in particular the pressure increases above 200 psia (including up to 367 psia) were due solely to the injection/withdrawal operating conditions of the well and not related to any loss of wellbore integrity related to the packer, tubing or casing. EPA, in a letter dated May 18, 2015, agreed that the annulus pressures observed to date were due primarily to thermal and injection pressure effects, rather than a loss of mechanical integrity. EPA recommended, and PG&E accepted, a maximum annulus pressure limit of 400 psia. In addition, EPA stipulated that if the annulus pressure exceeded 400 psia for a period greater than 24 hours, a notification must be made to the EPA followed by a written submission within 5 days of the pressure exceedance in accordance with Parts D.6.2.b and D.6.2.c of the permit.

The I/W well annulus pressure exceeded 400 psia for a period of 41.5 hours between May 31 and June 2, 2015. This was subsequent to the new annulus pressure limitation of 400 psia and during the final withdrawal flow testing of ambient air, which included a longer sustained withdrawal period than had previously been implemented. The 400 psia limitation was again exceeded during resumption of the final withdrawal testing on June 3 – 4, 2015; however, the withdrawal testing program ended on June 4, 2015, and the I/W well shut-in, before the exceedance reached 24 hours in duration. After the well was shut-in, the annular pressures fell below the 400 psia threshold consistent with the previously seen behavior where the pressure increases or decreases as a function of thermal effects.

At this point, PG&E's compression testing program is complete and the I/W well is scheduled to remain shut-in. Since the end of the compression testing program on June 4, 2015, the I/W well annular pressures have continued to decline and are expected to eventually return to the normal range under static shut-in conditions. As of the date of this report, the I/W well annulus pressure was less than 170 psia.

Pursuant to the conditions of the subject permit, PG&E submits this evaluation of the pressure exceedance described above, as to whether or not it represents a loss of mechanical integrity. For this evaluation, the graphs and exhibits in the previous May 14, 2015 submission are updated for the observed and calculated annular pressures since that last report. **EXHIBIT 1** is a graph of the observed variation in the I/W well annulus pressure and temperature since the start of injection operations on February 14 to June 5, 2015. The same graph of annulus pressure and temperature but focused on the recent period May 3 to June 5, 2015 is presented by **EXHIBIT 2**. A graph of the associated tubing pressure and injection/withdrawal rates is given in **EXHIBIT 3**.

Other previous diagnostic graphs of 1) the observed daily maximum annulus pressure versus maximum annulus temperature and 2) the maximum daily injection pressure versus maximum annulus pressure are updated from the May 14, 2015 report and presented by **EXHIBITS 4** and **5**, respectively. The additional data on these diagnostic plots further confirm the previous conclusions that there are no meaningful correlations to be made between these variables and the annulus pressure readings.

The pressure-temperature relationship developed previously by PG&E to predict the thermal effects on I/W well annular pressures is shown graphically by **EXHIBIT 6**. This relationship is based on the assumption that the primary factor affecting the annulus pressure is the thermal expansion, or contraction, of the confined annular fluids (KCL water). The change in water density as a function of the temperature will cause a change in the water volume in the annulus, increasing or decreasing the volume and pressure of the nitrogen cap which was placed on top of the annulus fluid (initially at 100 psia). The delta temperature used by this equation is calculated as the difference between the final average wellbore temperature, T_f[1] and the initial wellbore temperature, T_i established when the nitrogen cap was placed on the annulus (94.3 °F). The underlying methodology and equations presented in previous submittals are given in **EXHIBITS 7** and **8**.

Applying the above pressure-temperature relationship used in the May 14, 2015 evaluation, the predicted and observed annular pressures versus time are presented graphically in **EXHIBIT 9** for the recent period May 3 to June 5, 2015. The delta temperatures used in the exponential equation are shown in **EXHIBIT 10**.

The observed annular pressures in **EXHIBIT 9**, particularly those pressures greater than 400 psia, are shown to be consistent with the predicted pressures based on the available temperature data. The timing of the high and low peaks in annular pressure is generally in sync with the highs and lows for the predicted pressures. The pressure-temperature relationship is able to predict the two maximum pressures observed on June 2 and June 4, 2015, although better for the second than the first peak, again showing how the evaluation of the annular pressure-temperature response is very difficult to predict.

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[1] T_f is determined from an average of the surface well temperature and the bottomhole temperature. The bottomhole temperature is measured continuously by a surface readout gauge. The surface well temperature is determined in most cases as a 24-hr trailing average (less for cycling injection/withdrawal periods) of the variation in the measured I/W well annulus temperatures.

We believe that the annular pressure excursions above 400 psia are related to sustained high temperatures of the withdrawal air during the extended flow period. This is unlike previous evaluations where the annulus pressures were cycling daily in correlation to the ambient air, bottomhole temperature, and annulus temperature during air injection and during injection/withdrawal cycling. Based on the predicted annular pressures using the exponential function, it appears that the sustained release of hot air from the reservoir caused a steady heating of the annular fluids, resulting in a constant increase of the I/W well annulus pressure, which pressure increase was ended only by the termination of the withdrawal flow. Previous PG&E evaluations had concluded that the annular pressure could be expected to remain between 30 and 600 psia during the anticipated operating conditions solely due to thermal effects, which is now generally confirmed by the recorded annular pressures.

CONCLUSIONS AND LIMITATIONS

We have evaluated a number of key variables as a surrogate for the more complex system, and have curve matched the past relationship. While the operational process (e.g. injection flow versus withdrawal flow) appears to affect the magnitude of the annular pressure response, nevertheless, there is enough general agreement between the predicted and observed annular pressure trends and values in this updated evaluation to conclude that the observed annular pressure readings above 400 psia are solely a reflection of the thermal effects due to the extended withdrawal operating conditions and do not reflect a loss of mechanical integrity. This is reinforced by the fact that the annulus pressures are returning to the normal range under static shut-in and ambient air temperatures conditions.

The evaluation of annular pressure-temperature response is very complex and outside of the scope of a typical annular pressure-temperature monitoring program. Although it has significant predictive limitations, we believe our evaluation methodology is reasonable and defensible for the purpose of demonstrating maintenance of I/W well mechanical integrity and compliance with the UIC permit for the well. A full scientific evaluation would involve modeling more variables than a simple spreadsheet model can realistically handle (e.g., variations in mass flow, variations in heat flow due to instrument and ambient effects, temperature gradients, pressure gradients, thermal effects on casing and tubing, etc.). This is beyond the resources, scope and available data for investigation by PG&E.

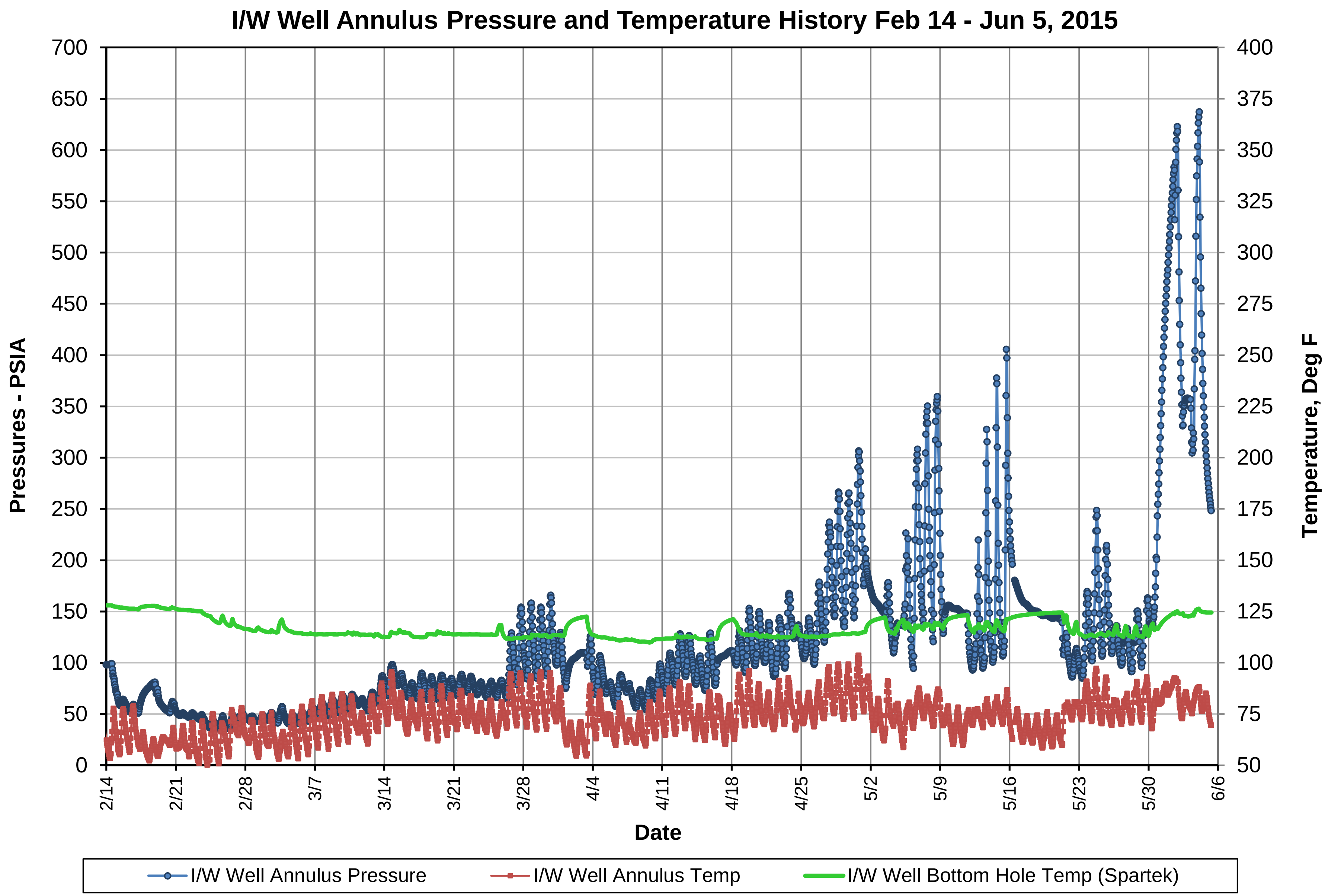
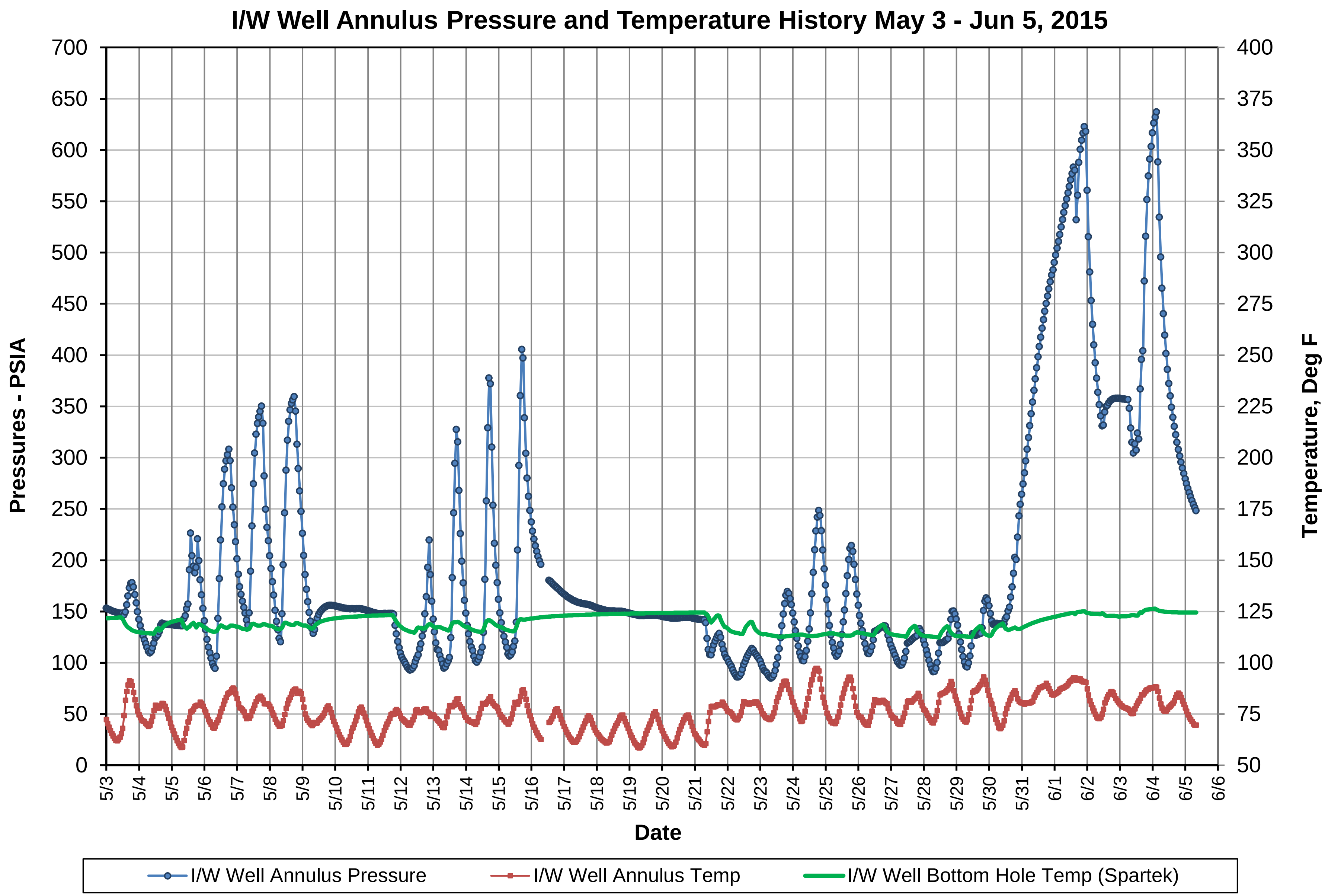

I/W Well Annulus Pressure and Temperature History Feb 14 - Jun 5, 2015
Pressures - PSIA
Temperature, Deg F
Date
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
50
75
100
125
150
175
200
225
250
275
300
325
350
375
400
2/14
2/21
2/28
3/7
3/14
3/21
3/28
4/4
4/11
4/18
4/25
5/2
5/9
5/16
5/23
5/30
6/6
I/W Well Annulus Pressure
I/W Well Annulus Temp
I/W Well Bottom Hole Temp (Spartek)

EXHIBIT 1


I/W Well Annulus Pressure and Temperature History May 3 - Jun 5, 2015
Pressures - PSIA
Temperature, Deg F
Date
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
50
75
100
125
150
175
200
225
250
275
300
325
350
375
400
5/3
5/4
5/5
5/6
5/7
5/8
5/9
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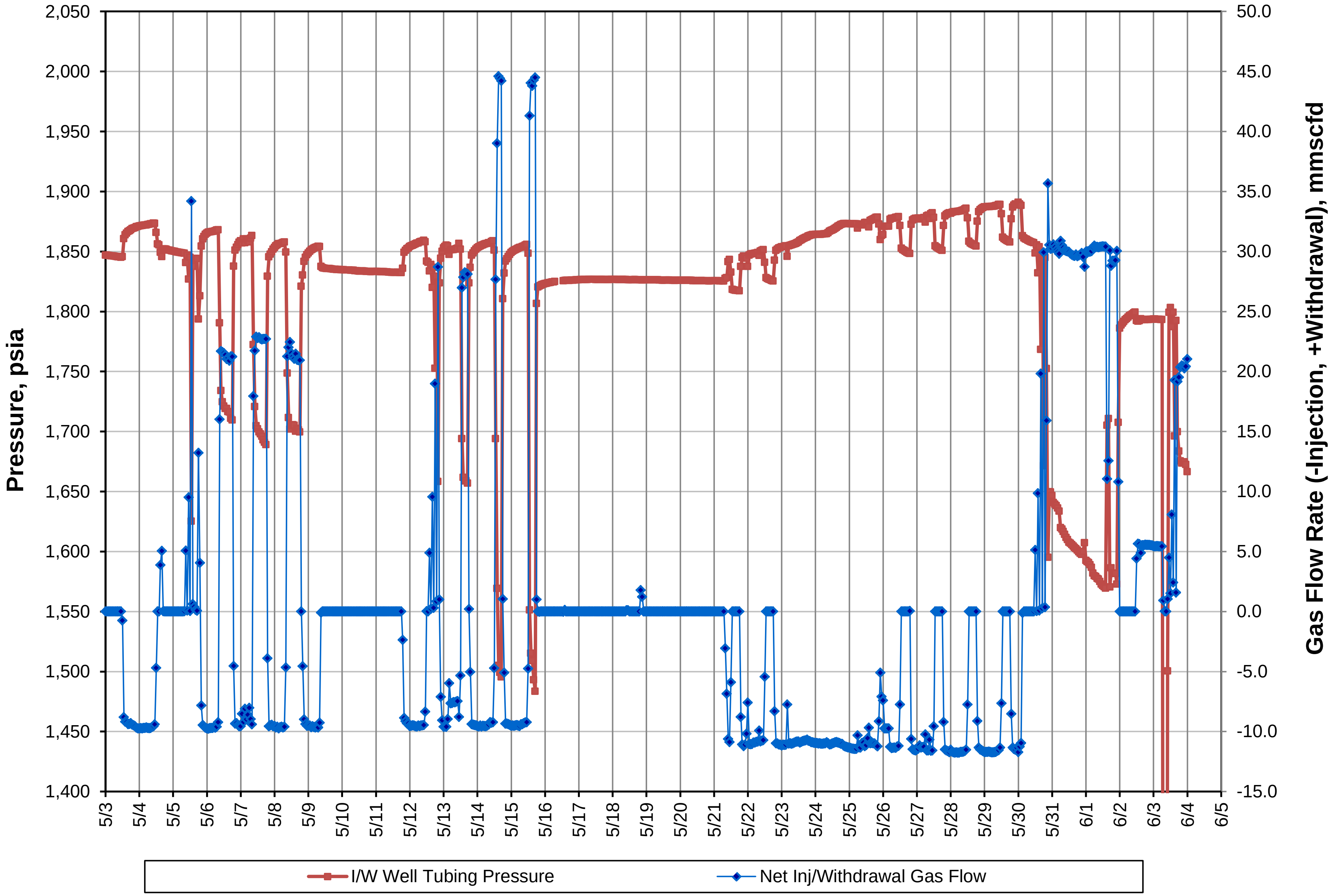
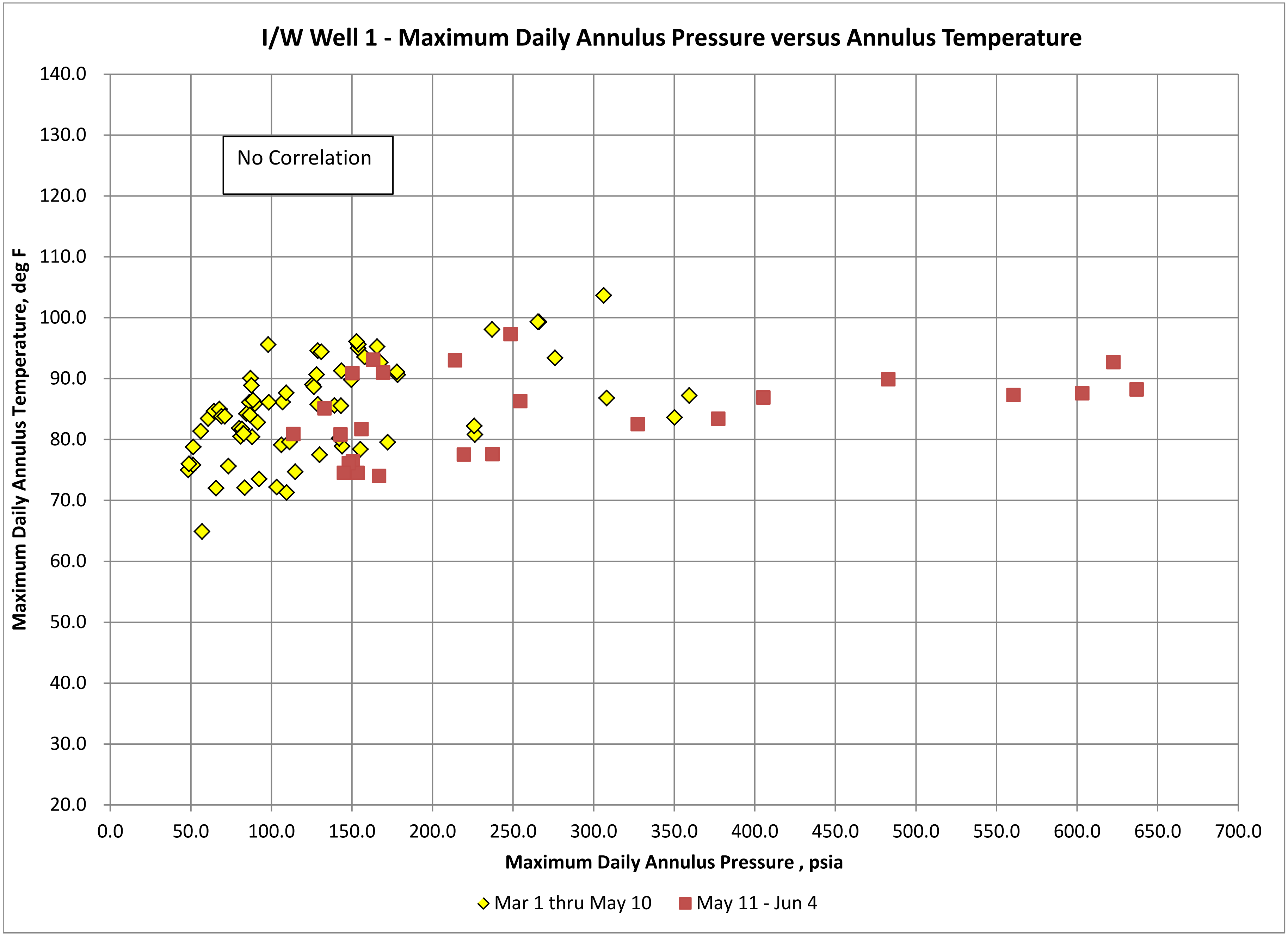
5/19
5/20
5/21
5/22
5/23
5/24
5/25
5/26
5/27
5/28
5/29
5/30
5/31
6/1
6/2
6/3
6/4
6/5
6/6
I/W Well Annulus Pressure
I/W Well Annulus Temp
I/W Well Bottom Hole Temp (Spartek)

I/W Well Tubing Pressures and Gas Flow Rate May 3 - Jun 5, 2015





I/W Well 1 - Maximum Daily Annulus Pressure versus Annulus Temperature
No Correlation
Maximum Daily Annulus Temperature, deg F
140.0
130.0
120.0
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
650.0
700.0
Maximum Daily Annulus Pressure , psia
Mar 1 thru May 10
May 11 - Jun 4

EXHIBIT 4

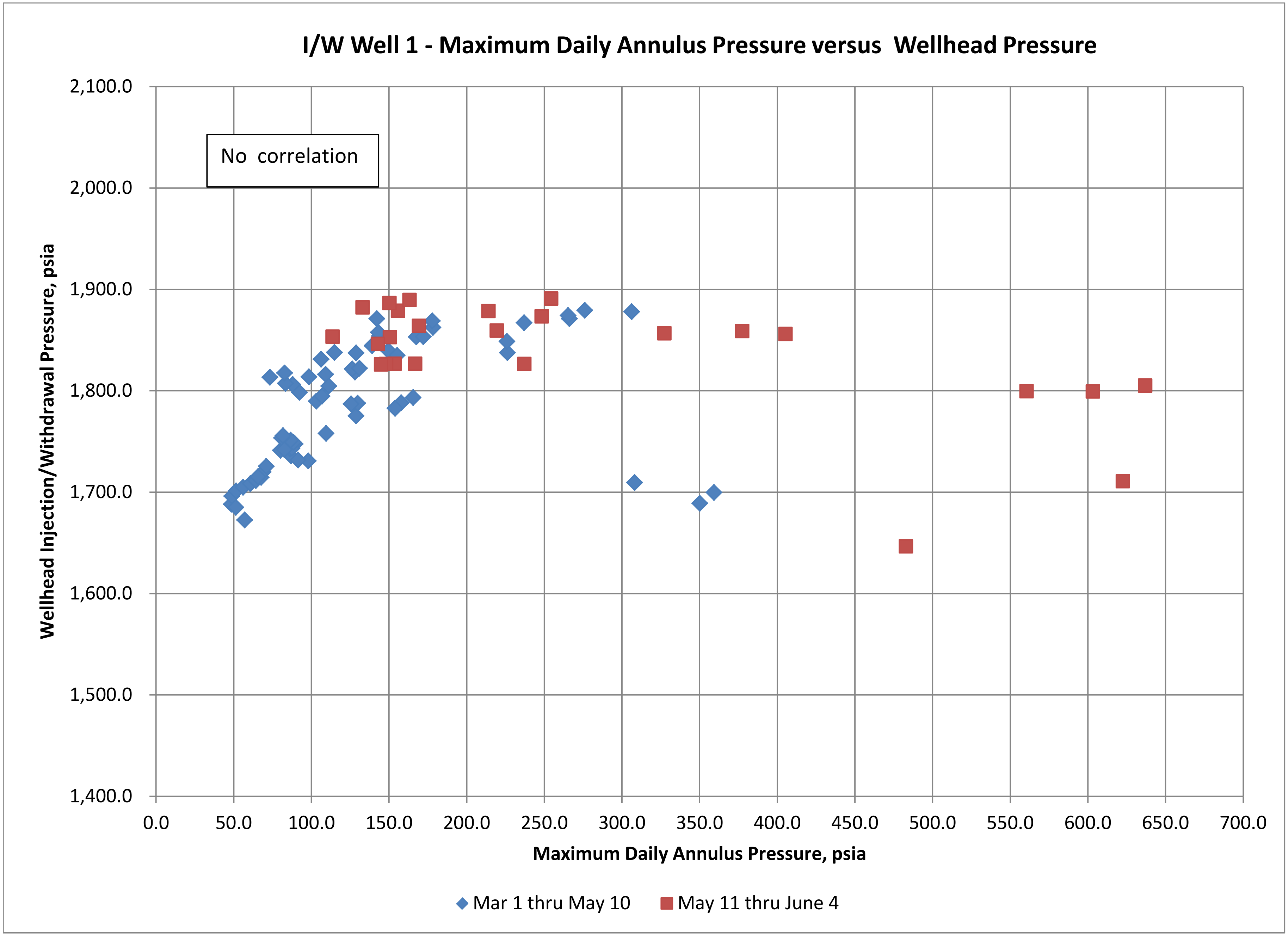

I/W Well 1 - Maximum Daily Annulus Pressure versus Wellhead Pressure
No correlation
Wellhead Injection/Withdrawal Pressure, psia
2,100.0
2,000.0
1,900.0
1,800.0
1,700.0
1,600.0
1,500.0
1,400.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
650.0
700.0
Maximum Daily Annulus Pressure, psia
Mar 1 thru May 10
May 11 thru June 4

EXHIBIT 5

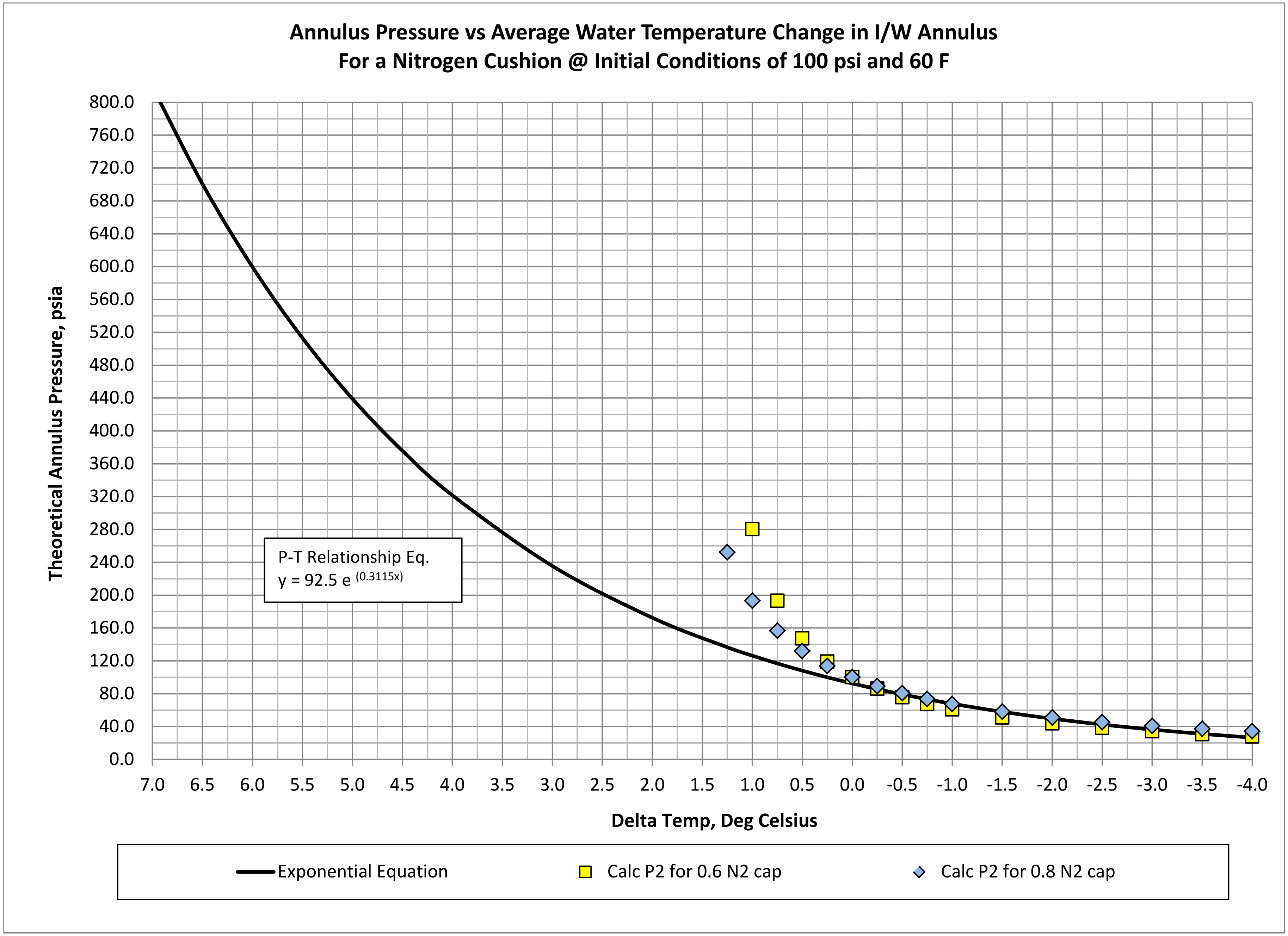
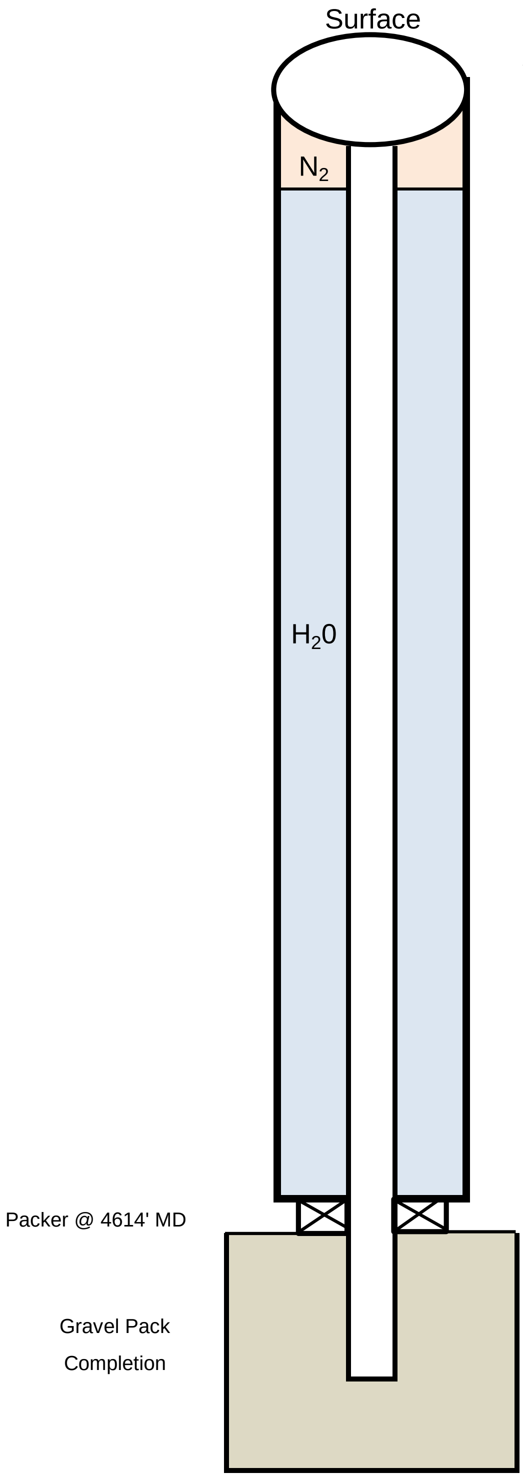

Annulus Pressure vs Average Water Temperature Change in I/W Annulus
For a Nitrogen Cushion @ Initial Conditions of 100 psi and 60 F
Theoretical Annulus Pressure, psia
800.0
760.0
720.0
680.0
640.0
600.0
560.0
520.0
480.0
440.0
400.0
360.0
320.0
280.0
240.0
200.0
160.0
120.0
80.0
40.0
0.0
7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0 -0.5 -1.0 -1.5 -2.0 -2.5 -3.0 -3.5 -4.0
Delta Temp, Deg Celsius
P-T Relationship Eq.
y = 92.5 e (0.3115x)
Exponential Equation
Calc P2 for 0.6 N2 cap
Calc P2 for 0.8 N2 cap

EXHIBIT 6

PG&E Test I/W Well 1 Annulus Pressure Calculations



Assume that the water in the annulus acts like a piston on the N_2 cap.

The change in water density (ρ) as a function of temperature is:

$$\rho_{wf} = \rho_{wi} / [\, 1 + \beta\, (\, T_f - T_i)\,]$$

but, ρ = mass/vol and mass is constant; therefore:

$$\frac{1}{V_{wf}} = \frac{1}{V_{wi}} / [\, 1 + \beta\, (\, T_f - T_i)\,]$$

$$V_{wf} = V_{wi} \times [\, 1 + \beta\, (\, T_f - T_i)\,]$$

$$\Delta V_w : V_{wf} - V_{wi}$$

Where:

- V_{wi} = Initial water volume, m^3
- V_{wf} = Final water volume, m^3
- Ti = Initial water temperature, ^0C
- Tf = Final water temperature, ^0C
- β = Volumetric temperature co-efficient of water, $m^3/m^3\ ^0C$
  (www.engineeringtoolbox.com)

For N_2 cushion**:**

PV = z n R T

P_1 = 100 psi

$$P_2 = \frac{z\, n\, R\, T_2}{V_2} \longrightarrow N_2 \text{ volume adjusted for } \Delta V_w$$

I/W Test Well Annulus Pressure Calculations based on the change in Water Density as a Function of Temperature

<u>ASSUMPTIONS & INPUT PARAMETERS</u>

Annular space between 9-5/8" 40# and 5-1/2" 17# pipe =	0.2607	cuft/ft
Length of annular space (packer @ 4614' MD) =	4,614.0	ft
Total annular space =	1,202.9	$feet^3$
Total annular space =	214.2	barrels
Estimated initial wellhead volume available for N2 =	0.80	cuft
P1 = Initial pressure of N2 =	100.0	psia
T1 & T2 = temperature of N2 =	60.0	F
z factor for N2 @ 100 psi and 60 deg F =	0.995	
No of moles N2 =[100 psia x N2 cuft]/[0.995 x 10.732 x (460+60)] =	0.0144	moles

Volumetric Temperature Coefficient of Water, β (www.engineering toolbox.com)

Deg C	Deg F	β, m3/m3 deg C
10.0	50.0	0.000088
20.0	68.0	0.000207
30.0	86.0	0.000303
32.2	90.0	0.000321
40.0	104.0	0.000385

	0.000321							P2 = znR(T2)/(V2)		$y=92.5e^{0.3115x}$
delta Temp, deg C	β	delta Vol, m3	Vwi, m3	Vwf, m3	Delta Vol, m3	Delta Vol, cuft	V2, cuft	Calc P2 for 0.8 N2 cap	Calc P2 for 0.6 N2 cap	Exponential Equation
7.00										818.69
6.50										700.62
6.00										599.57
5.50										513.09
5.00										439.09
4.50										375.76
4.00										321.57
3.00										235.50
2.00										172.47
1.25	0.000321	1.000401	34.0617	34.0753	0.013667	0.482652	0.317348	252.09		136.54
1.00	0.000321	1.000321	34.0617	34.0726	0.010934	0.386121	0.413879	193.29	280.53	126.31
0.75	0.000321	1.000241	34.0617	34.0699	0.008200	0.289591	0.510409	156.74	193.29	116.84
0.50	0.000321	1.000161	34.0617	34.0671	0.005467	0.193061	0.606939	131.81	147.44	108.09
0.25	0.000321	1.000080	34.0617	34.0644	0.002733	0.096530	0.703470	113.72	119.17	99.99
0.00	0.000321	1.000000	34.0617	34.0617	0.000000	0.000000	0.800000	100.00	100.0	92.50
-0.25	0.000321	0.999920	34.0617	34.0589	-0.002733	-0.096530	0.896530	89.2	86.1	85.57
-0.50	0.000321	0.999840	34.0617	34.0562	-0.005467	-0.193061	0.993061	80.6	75.7	79.16
-0.75	0.000321	0.999759	34.0617	34.0535	-0.008200	-0.289591	1.089591	73.4	67.4	73.23
-1.00	0.000321	0.999679	34.0617	34.0507	-0.010934	-0.386121	1.186121	67.4	60.8	67.74
-1.50	0.000321	0.999519	34.0617	34.0453	-0.016401	-0.579182	1.379182	58.0	50.9	57.97
-2.00	0.000321	0.999358	34.0617	34.0398	-0.021868	-0.772242	1.572242	50.9	43.7	49.61
-2.50	0.000321	0.999198	34.0617	34.0343	-0.027334	-0.965303	1.765303	45.3	38.3	42.46
-3.00	0.000321	0.999037	34.0617	34.0289	-0.032801	-1.158364	1.958364	40.9	34.1	36.33
-3.50	0.000321	0.998877	34.0617	34.0234	-0.038268	-1.351424	2.151424	37.2	30.7	31.09
-4.00	0.000321	0.998716	34.0617	34.0179	-0.043735	-1.544485	2.344485	34.1	28.0	26.61
-4.50	0.000321	0.998556	34.0617	34.0125	-0.049202	-1.737545	2.537545	31.5	25.7	22.77

$$V_{wf} = V_{wi} \times [1 + \beta (T_f - T_i)]$$

V_{wi} = Initial water volume, m^3

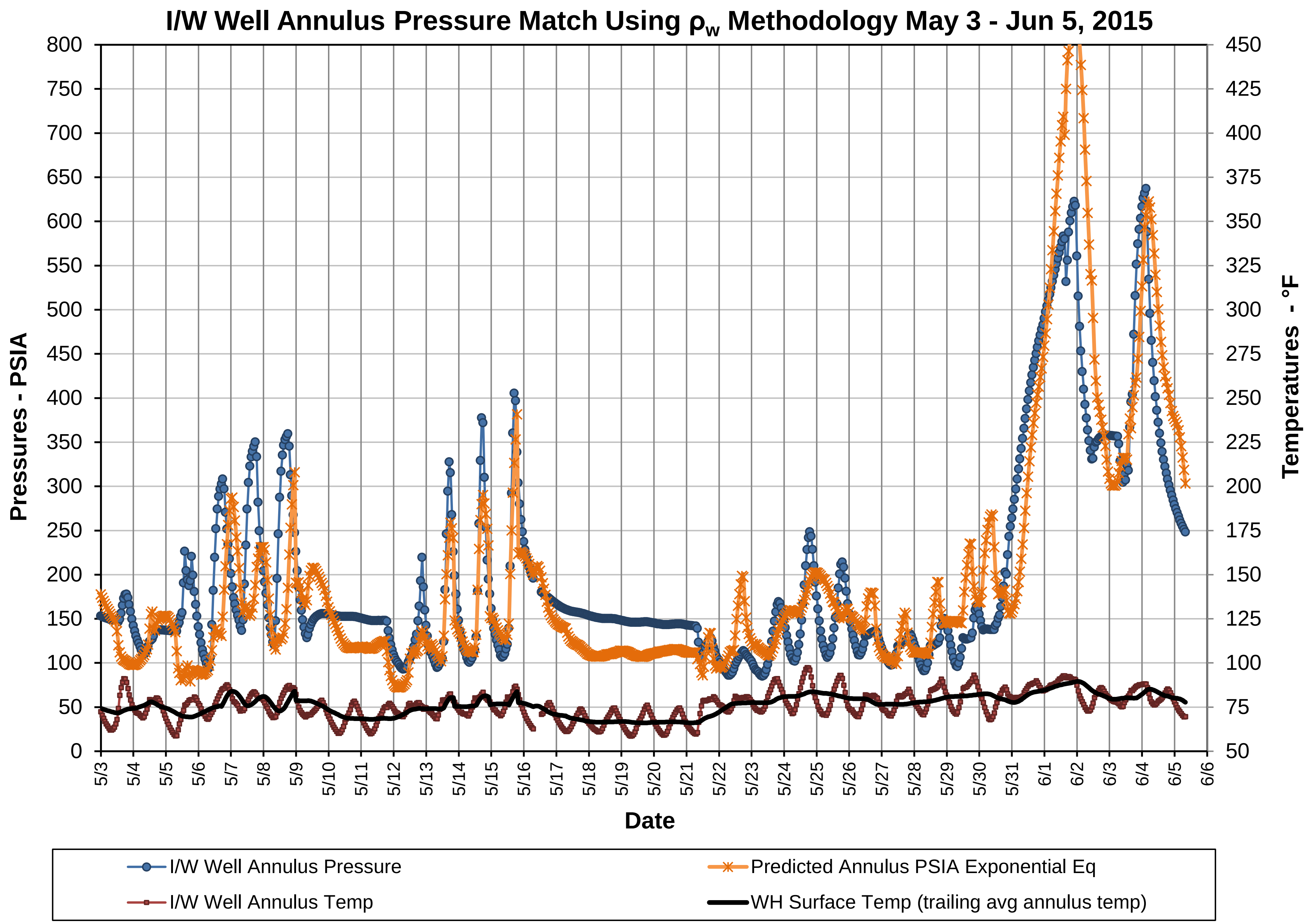
V_{wf} = Final water volume, m^3

Ti = Initial water temperature, ^0C

Tf = Final water temperature, ^0C

β = Volumetric temperature co-efficient of water, $m^3/m^3\ ^0C$

EXHIBIT 8


I/W Well Annulus Pressure Match Using ρ_w Methodology May 3 - Jun 5, 2015
Pressures - PSIA
Temperatures - °F
Date
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
450
425
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
5/3
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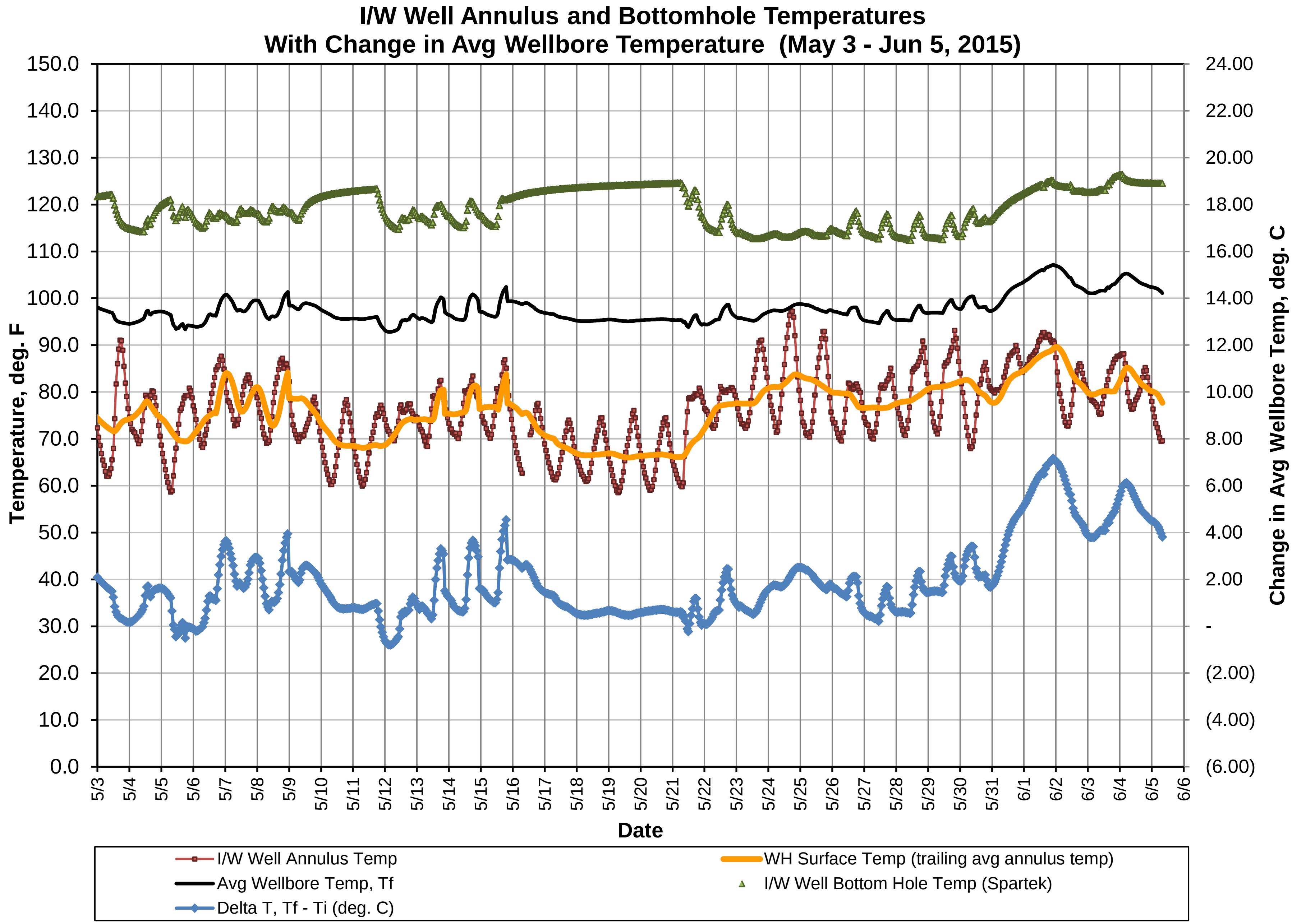
5/19
5/20
5/21
5/22
5/23
5/24
5/25
5/26
5/27
5/28
5/29
5/30
5/31
6/1
6/2
6/3
6/4
6/5
6/6
I/W Well Annulus Pressure
Predicted Annulus PSIA Exponential Eq
I/W Well Annulus Temp
WH Surface Temp (trailing avg annulus temp)


I/W Well Annulus and Bottomhole Temperatures
With Change in Avg Wellbore Temperature (May 3 - Jun 5, 2015)
150.0
140.0
130.0
120.0
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
Temperature, deg. F
24.00
22.00
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
-
(2.00)
(4.00)
(6.00)
Change in Avg Wellbore Temp, deg. C
5/3
5/4
5/5
5/6
5/7
5/8
5/9
5/10
5/11
5/12
5/13
5/14
5/15
5/16
5/17
5/18
5/19
5/20
5/21
5/22
5/23
5/24
5/25
5/26
5/27
5/28
5/29
5/30
5/31
6/1
6/2
6/3
6/4
6/5
6/6
Date
I/W Well Annulus Temp
Avg Wellbore Temp, Tf
Delta T, Tf - Ti (deg. C)
WH Surface Temp (trailing avg annulus temp)
I/W Well Bottom Hole Temp (Spartek)